Gain Controlling of Erbium-Doped Fiber Amplifier by Samarium Doped Inner-Cladding in the 1.5 µm Region

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Characteristics of a new type of erbium-doped fiber for optical amplifiers were reported where erbium was doped in the center of the core and samarium doped in a ring of the cladding. Using samarium absorption of photons around 1.5 µm in the erbium ion emission range, we demonstrated a new way of controlling the gain spectrum of erbium-doped fiber amplifier without using external filters. Amplifier small signal gain under saturation was about 11 dB and within 2.3 dB variation in the range of 1520–1560 nm. Total output power from the amplifier was 9 dBm with 100 mW of pump power at 980 nm. The effects of samarium-doped inner cladding on amplified spontaneous emission spectra in the long wavelength band were also reported.

Keywords erbium-doped fiber amplifier (EDFA), gain flatness, optical amplifier, samarium

In wavelength division multiplexing (WDM) systems, spectral characteristics of optical amplifiers are important parameters that will determine the overall transmission capacity. One of critical issues in erbium (Er)-doped fiber amplifier (EDFA) is the spectral flatness in the gain bandwidth. To achieve a flat gain spectrum several techniques have been developed such as long period gratings (LPG) [1], acousto-optic tunable filters (AOTF) [2], and changing glass host material [3]. As alternative ways, there are hybrid fiber methods such as several segments of erbium-doped fibers with different glass hosts [4] and samarium (Sm)-doped optical fibers in a serial configuration with conventional EDF where separate segments of Sm-doped fibers are located in the middle or at the end of EDF [5–7]. These serial segment techniques, however, need more than two fibers doped with different compositions and the
optimization process requires a rather tedious variation of parameters of individual optical fibers.

In our previous studies we proposed a new type of optical amplifier fiber to achieve the built-in suppression of the gain peak at 1.53 μm in a single optical fiber [8–9]. The proposed method was based on designing a single optical fiber where the core is doped with Er, while some portion of the inner cladding is doped with Sm. From interaction between the evanescent field and samarium ions in the inner cladding, in-line filtering of optical signal could be achieved without external filters. In this paper, we report detailed measurements on several characteristics of the proposed fiber amplifier.

The Structure of the Er-Doped Core and Sm-Doped Inner Cladding Fiber

In Figure 1, the erbium emission and samarium absorption spectra are shown. Sm ions have a negligible absorption at 980 nm while high absorption is around 1400, 1480, and 1570 nm. The absorption slope of Sm in the wavelength is longer than the 1480 nm peak can attenuate Er emission, especially the peak at 1530 nm.

The structure of the proposed fiber (Er/Sm fiber) is schematically shown in Figure 2. The proposed fiber preform was prepared using modified chemical vapor deposition (MCVD) along with a solution soaking method [10]. After conventional depositing outer cladding layers, we deposited a porous inner cladding layer to dope Sm to result in a ring layer with a certain thickness as shown in Figure 2. In the consolidation process of the doped inner cladding, reactant gases of CF₄ and POCl₃ were flown with care to match the refractive index of the doped layer to that of the outer cladding layers. After the Sm-doped inner cladding layer, conventional cladding layers were further deposited to control the diameter of the Sm-doped ring. Subsequently, a porous core layer was deposited for Er doping. The calculated numerical aperture and cut-off wavelength were 0.1 and 900 nm, respectively. The fiber had the core diameter of 3.32 μm. Note that the 980 nm pump, as shown in

![Figure 1. Sm absorption and Er emission spectra.](image)
Figure 2. The structure of the Er/Sm fiber.

Figure 2, has negligible overlap with the Sm-doped ring while the 1530 nm light has a significant overlap. Thus, the pump light is transparent to the samarium-doped ring, while the light near 1530 nm suffers from attenuation. As the stimulated and spontaneous emission are amplified along the erbium-doped core, overall gain near 1530 nm will be suppressed by the interaction of the evanescent field with the Sm-doped ring. The most significant parameters to control the gain shape are the location and width of the Sm-doped ring, the concentration of Sm, as well as that of Er in the core. The concentration of Er and Sm were estimated to be 1000, and 100 ppm, respectively. The width of the samarium ring was 2 microns.

Characteristics

Absorption profiles were measured with a cutback method for various fiber lengths, which is shown in Figure 3. The measured peak values are located between 62 and 63.5 dB/m plotted by solid lines adjusted to be the same at 1650 nm. The shape is somewhat changed in comparison with that of commercial EDF (dotted line).

Optical amplifiers were constructed using Er/Sm fibers of different lengths. The optimized length of the fiber was about 114 cm for 100 mW pumping at 980 nm. The output power was 9 dBm for 0 dBm input signal at 1550 nm. Under this saturation, −35 dBm probe signal scanned small signal gain. The average small gain within the conventional gain band, 1540–1560 nm was measured to be 11 dB with the variation less than 2.3 dB as shown in Figure 4. Compared with conventional EDFA, a significant reduction of gain in the 1530 nm region was obtained; however, the valley at 1540 nm and the power conversion efficiency of the fiber are not fully optimized yet.

To investigate the evident effect of Sm doping in the inner cladding, we measured the amplified spontaneous emission (ASE) of a long band region. In Figure 5(a) measured ASE spectra are shown for the length range of 246 to 803 cm. As the fiber length increased, the ASE power level was found to decrease due to low population inversion rate. The ASE power level, however, was lower than that of a commer-
Figure 3. Absorption of Er/Sm-doped fiber (solid lines) versus commercial EDF (dotted line).

Figure 4. Gain variation of small signal gain under saturation with 0 dBm tone at 1548 nm and –35 dBm of probe signal.

cial EDF in Figure 5(b) and a deep valley around 1580 nm were observed obviously. As shown in Figure 1, Sm has a absorption peak around 1580 nm and the valley in the ASE spectra is attributed to this Sm absorption peak. The commercial EDF was HE 980 and the length varied from 136 to 336 nm. The pumping power was 100 mW at 980 nm.

Discussions and Further Research

In the proposed fiber structure, the evanescent field of 1530 nm ASE was found to interact with Sm-doped ring to result in reduction of ASE and gain. It is also noted that the absorption spectrum of Er is also changed to a certain extent.
especially in the shorter wavelength region. It is believed that Sm ions in the inner cladding could have added insertion loss. In the case of small signal gain characteristics in the conventional EDFA gain band, 1530–1560 nm, the Er/Sm fiber showed a strong potential to control the gain of Er ions within a single fiber. This technique could obviate external filters and their control units in the amplifiers such that the management cost of amplifier modules could be significantly reduced in the communication systems. The average gain of the optical amplifier was comparable to those of previous studies based on serial segments of samarium doped fibers [5–7]. However, the pump efficiency was not fully optimized in the proposed fiber structure. First, the Er ion concentration, 1000 ppm relative to SiO₂, was rather high enough to induce cross relaxation among Er ions. Next, even though there is a buffer layer between the Er-doped core and Sm-doped ring, it is quite possible to have an overlap of ions near the core due to diffusion in the high temperature diffusion process. This overlap may induce residual loss of Sm in the Er emission process. And also the small but finite absorption cross section of pump light at 980 nm is Sm ions can
reduce the pump efficiency for Er ions. Consequently, Er concentration should be reduced to increase the power conversion efficiency, and a more optimized waveguide structure also be studied to reduce pump absorption and residual absorption. In the long band of EDFA, the addition of a samarium ring structure was found to deteriorate the gain flatness. Thus, the proposed structure might be restricted to conventional EDFA band.

Conclusion
The characteristics were measured for the new EDF to generically control the gain of optical amplifier by introducing samarium doped inner cladding. In the wavelength range of 1530–1560 nm, less than 2.3 dB variation for average 11 dB gain was achieved without using external filters under the saturation condition of 9 dBm output power. In the wavelength range of 1560–1620 nm, the samarium-doped ring caused a decrease in amplified spontaneous emission power around 1580 nm. Optimization of the location of the samarium-doped ring, as well as doping concentration and ring thickness, are being pursued for further improvement.

References
Biographies

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